

## Energy Saving in Pilger Mill Electric Drives. Complete Solution

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### ABSTRACT

This paper considers issues related to increasing energy efficiency in electric drives of pilger rolling mills, presenting kinematics of such mills, provides justification for the general load chart, presents the detailed review of reference materials on technical energy saving solutions, and suggests a math model of an electric drive with a field regulated reluctance machine. The paper suggests key methods of saving energy in electric drives of pilger mills, namely: kinematic scheme improvement; main energy drainers and ways of energy loss reduction in electric drives with direct- and alternate-current motors, energy-saving electric drive control profiles. The article compares energy-saving resources in electric drives with various-type motors (direct-current motors, synchronous motors, and field regulated reluctance machine), clarifies the scheme of energy-saving resource implementation, provides the qualitative evaluation of electric drive control method efficiency. The accent is made on high energy efficiency of the proportionate control of armature and excitation circuits and across the range of torque in electric drives of abruptly-variable-load mills. The highest economic effect is reached in the electric drive with a field regulated reluctance machine – by means of implementing the energy-efficient electromechanical converter and applying energy-saving control profiles.

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## 1. INTRODUCTION

Seamless pipes (casing, drill, tubing, cracking, oil line, etc.) are widely used in oil production and refining, heat energy and chemical industry, and machine engineering, aircraft and vehicle production, as well as in civil and industrial building. Quality requirements may vary depending on the purpose of pipes, so there are several consequent technological stages of rolling: piercing, plugging, and high-quality pipe rolling. The motion nature of actuators of pilger rolling machines (piercing mills, pilger mills, cold rolling mills) is complex and unusual, and the load torque is not evenly distributed across a rolling cycle.

The existing methods of improving energy efficiency of electric drives include using electric drives with enhanced performance coefficient, transition to a regulated electric drive, rational selection of the electromechanical converter's installed power, selection of an electric drive control profile. In scientific papers, the abovementioned methods are considered as industry-general mechanisms for standard operation of an electromechanical converter.

A good many papers were devoted to methods of electric loss reduction in drives with various-type motors – the most renowned of them were made by I.I. Petrov [1], N.F. Ilyinsky [2, 3], B.S. Leznov [4, 5], O.V. Kryukov [6], Yu.S. Usynin [7], I.Ya. Braslavsky [8], V.N. Polyakov [9, 10], Giovanni De Filippis [20], T. Ahonen [21], M. A. Saidel [22], A. Zabardast [23]. Of special note is the series of works on energy saving in metal industry electric plants: rolling mills (A.S. Karandaev [11], V.F. Buryanov [12], V.R. Khrashin

[13, 14]), arc steel furnaces (G.P. Kornilov [15]), draft equipment (Yu.S. Usynin [16], O.V. Kryukov [17]), general issues on energy saving at metal industry enterprises (G.V. Nikiforov [18], V.K. Oleynikov [19]).

As seen from the review of scientific references, the problem of energy saving in electric drives turns out to be complex and even quite ambiguous. Thorough studying of specifics of operation and technical structure of pilger mill electric drives stimulates considering the following issue from the perspective of energy-saving: these machines are unique equipment of high-power (in MWs) engines characterized by the extremely uneven load distribution chart; there, severe torque overloads go with idleness periods of an electric drive. In such conditions, energy saving on the mill is complicated and requires deep preparatory analysis, as well as a complex approach to implementation energy-saving methods. The increasing demand for seamless pipes (shown in atomic industry, aircraft industry, etc.), significant share of energy consumption by pilger mills, and – practically – depreciation of electrotechnical equipment, the scientific-technical problem of improving energy efficiency of electric drives on considered rolling pipes becomes acute.

During the work, key provisions of the electric machines theory, electric drive theory, semiconducting converter equipment theory, automated control frequency methods, computer-assisted math system modeling methods, and the finite element method were used.

## 2. RESEARCH METHOD

### 2.1. Math Model of a Rolling Mill

Usually, the mathematical description of electric drives and associated technological objects is given with due attention to assumptions that allow for simplifying the mathematical technique. For instance, an electric motor is presented as a lumped-parameter system. Such an approach is reasonable in the context of math modeling of an electric drive with traditional-type electromechanical converters. From the point of energy efficiency of DC-electric drives and synchronous ones, as well as considering the existing detailed analytical basis, typical math models can be used and provide calculation of total losses and their elements with a reasonable degree of accuracy [24, 25].

Absence of real design methodologies and practical recommendations in the context of developing new types of electromechanical converters drives the necessity to consider the distribution of system constants [26]. In the existing technical publications and other sources, no models for determining components of losses in electric drives with field regulated reluctance machine (FRRM) were found. The existing math models of an electric drive with FRRM describe and ascertain either the motor operation mode with consideration of magnetic fields in the electric machine [27, 28], or specifics of FRRM-drive parameter regulations — particularly in cases when it is required to show higher performance [29]. In this paper we suggest a math model that, as far as we are concerned, is able to solve the problem. The model distinguishes itself since it applies loss components assumed for all motors, but ascertained considering structural and FRRM operation specifics.

Math models used for qualitative estimation of losses in considered electric drives contain the following units: a system's mechanical part (reducer, gear stand); electromechanical converters (direct-current motor, synchronous motor or FRRM); semiconducting converters (thyristor direct-current converter, frequency converter, multiphase semiconducting converter), loss component estimation unit.

### 2.2. Math Model of a Mechanical Part

Mathematical description of mechanics and pilger rolling technology are comprehensively described in [30]. Due to that, ready models of a mechanical part described in [30] were used. Generally, they consist of two main blocks: a mechanical converter (reducer, gear stand) and the load chart formation block. The static load torque for a cold rolling mill 450 was determined in the following way:

$$M_s = q \cdot \gamma \cdot r_{cr} \frac{M_{\Sigma \text{for}(\text{rev})}}{\rho_g \cdot \eta}; \quad (1)$$

$$M_{\Sigma \text{for}} = P_{av} \cdot \rho_r \left( n_Q + \eta_d \sqrt{\frac{1,4 \cdot \Delta t_{av}}{\rho_r}} \right); \quad (2)$$

$$M_{\Sigma \text{rev}} = 0,85 P_{av} \cdot \rho_r \left( \eta_d \sqrt{\frac{0,6 \cdot \Delta t_{av}}{\rho_r}} - n_Q \right) \quad (3)$$

where  $M_s$  stands for static motor load torque;  $M_{\Sigma \text{for}}$  for forward rolling torque;  $M_{\Sigma \text{rev}}$  for reversal rolling torque;  $q$  for coefficient of idle-time torque loss;  $\rho_g$  for leading gear's initial radius;  $\eta$  for performance coefficient;  $r_{cr}$  for crank radius;  $\gamma$  for coefficient depending on mill's dynamics and structure;  $P_{av}$  for average total pressure during rolling;  $\rho_r$  for roll radius;  $\eta_d$  for deformation zone shape factor;  $\Delta t_{av}$  for average rolling draft.

The math model of a mechanical part of a cold rolling mill 450 is given, presented as a system of two main blocks: a mechanical converter (I) and load chart formation block (II). Block I describes processes in the mechanical part considering the variable gear ration. Based on the initial rolling route data, Block II forms the electric drive load chart, as well as coordinates torques with the rolling machine angle. Initial data (rolling and idle time torques, forward and idle stroke duration, cycle period) for formation of load charts of cold rolling mill 450 were obtained from authorized representatives of the Chelyabinsk pipe rolling plant's electrotechnical services.

### 2.3. Math Model of an Electric Drive with FRRM

When modeling non-typical electromechanical converters, distribution of magnetic induction both in overload zones and at normal load values. In order to take this into account, an electric motor's magnet core is broken down into elements to be considered separately, with a system of differential equations based on Maxwell's laws given for each one. By using the finite-difference and finite-element methods, it is possible to calculate the system of differential equations with distributed constants [26].

To date, numerous software products are empowered to calculate electromagnetic systems by virtue of the finite-element method (FEMLAB, ANSYS, ELCUT, etc.). As these products are equipped with the already-developed calculation algorithms is needed from a math model developer is to set the electric motor geometry, select and lay boundary conditions, and determine the kind and number of finite elements. If a user needs to calculate running values (currents, voltages, torque) that depend on the system of controlling actions and parameters of an electromechanical converter, the problem grows more complex. When selecting a math modeling product, the following factors were considered: availability of electromagnetic torque calculation unit based on Maxwell's stress tensor methodology, possibility of correct estimation of total losses and their components by means of both default software tools and user algorithms.

The math model of the FRRM-based "Electric Drive – Rolling Stand" system was generated in *Ansys Simplorer/Maxwell* and given in Figure 1. It contains the following blocks: SC – speed controller; SS – speed sensor; model of a mechanical part of a rolling mill 450; CU – motor shaft angle conversion unit; PS – position sensor; PCFU – phase current formation unit; CR1...CR6 – phase current regulators; the model of an electromechanical converter's magnetic system and a loss component determination unit. The loss component determination unit was created within the model as an APDL code.

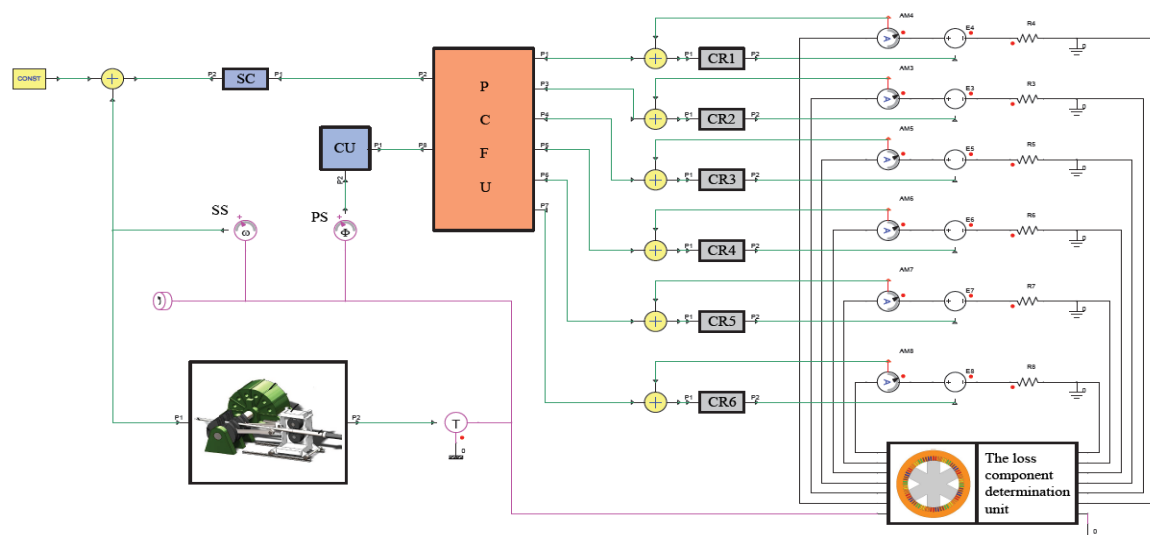


Figure 1. Ansys Simplorer/Maxwell Math Model of the FRRM-Based "Electric Drive – Rolling Stand" System

### 3. RESULTS AND ANALYSIS

#### 3.1. Energy Efficiency Enhancement

Rolling of a heated blank to a shell starts at piercing mills and is conducted by double-cone work rolls rotating in the one direction. As a result, the blank has both rotational and translational motion, as roll axes are set at a certain angle to the rolling line. At the entrance cone, metal is prepared for piercing on the punch, and at the exit cone the interior surface of a shell is smoothed. Reciprocating rolling mills (pilger mills, cold seamless pipe rolling) have the effective roll radius in the cross-section. The rolling is conducted on the cone-share punch at the alternating motion of the rolling machine. Rolls do not make contact with the blank at limit positions, thus allowing for performing of auxiliary operations (pipe delivery and turning).

Initial technological parameters of a piercing mill, for instance, were drive armature circuit current oscillogram based on tracing of rolling of 886 bars. The arithmetic mean value of currents was taken as 100%. With that, the absolute value of relative divergence of registered values from the average came to  $\Delta I_{AV} = 0.058$ , while statistic dispersion of relative current divergence amounted to  $\sigma^2 = 0.0056$ . The divergence range (a difference between min and max registered value) of the armature current during rolling came to 32% of  $I_{AV}$ .

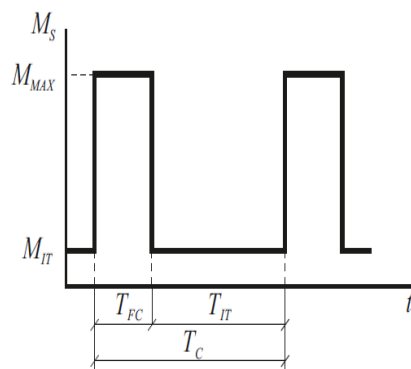


Figure 2. General chart for main electric drive of mill groups

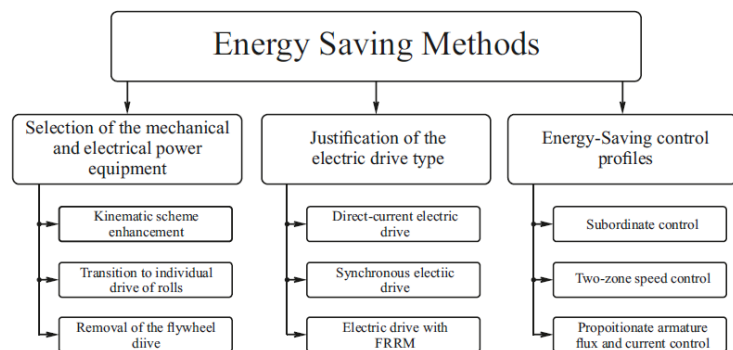


Figure 3. Main energy saving methods in pilger mill electric drives

Table 1 gives the examples and generalizes parameters of load charts of considered rolling mills. With that, the rolling cycle consists of two stages: a forward stroke and an idle stroke Figure 2.

Table 1. Parameters of Pilger Mill Load Charts

Mill Type	Load Chart Parameter and Numerical Value				
	$T_c$ (s)	$T_r$ (s)	$T_{idle}$ (s)	$M_{max}$	$M_{idle}$
Piercing	300	60	240	1.8	0.11
Pilger	2.8	1.1	1.7	1.7	0.10
Mill 450	3 ... 1.5	0.9 ... 0.45	2.1 ... 1.05	1.4	0.15

Parameters:  $T_c$  stands for single rolling cycle time (in seconds);  $T_r$  for rolling time (in seconds);  $T_{idle}$  idle stroke time (in seconds);  $M_{max}$  и  $M_{idle}$  for maximum torque for a rolling cycle and idle stroke torque (ratio of a rolling motor's torque rating). The existing data allow for plotting a general chart for considered mill groups in Figure 2, which was further used for analysis. This paper suggests the following energy saving methods on pilger mills: selection of mechanical and electrical power equipment, selection and justification of the electric drive type and profiles of electric drive control with lowest possible energy consumption in Figure 3.

#### 3.2. Selection of Electrical Power Equipment

Kinematic circuits in existing pilger mills increase energy losses (gear stand, flywheel). In order to reduce current rushes in power circuits rolling motors and power networks, flywheel drive is used on these mills (for instance, a flywheel of 9 m in diameter and 120 tons in weight is installed on a pilger mill) – such a

structure not only loads the electric drive and increases idle stroke losses, but also decreases reliability of bearing assembly operation. Capabilities of modern control means are advanced enough to delegate most issues related to implementation of actuator motion laws to an electric drive, thereby simplifying kinematic relations (for instance, it becomes possible to remove a gear stand on piercing and pilger mills) and applying an individual electric drive of rolls, which extends the range of possible motion control profiles in Figure 3. According to preliminary estimates, removal of a gear stand and flywheel on a pilger mill will be able to save up to 5% of the electric drive's power rating.

### 3.3. Justification of a Rational Type of an Electric Drive

The selection of an electric drive type was ground on a static model composed based on the balance equation for energy loss components in a motor:

$$P_1 = P_2 + \Delta P, \quad (4)$$

where  $P_1$  stands for electric motor power;  $P_2$  for roll power;  $\Delta P$  for total losses in an electric drive.

In order to make this model work efficiently, a large group of technical data associated with AC/DC motors of rolling mills (more than 500, published in [31]) was statistically treated. In these data, total losses were presented as systems of the following components:

$$\Delta P = P_{el} + P_{mag} + P_{mech}, \quad (5)$$

where  $P_{el}$  stands for electrical losses in a motor;  $P_{mag}$  for magnetic losses;  $P_{mech}$  for mechanical losses.

Qualitative evaluation of total losses and their components in considered types of electric drives revealed FRRM to be most energy-efficient for the simplest armature coil structure and absence of an excitation coil. In comparison to the existing solution (direct-current electric drive), application of an energy-efficient electromechanical converter may lead to saving up to 7% of the electric drive's power rating.

### 3.4. Energy-Saving Control Profiles

When calculating energy efficiency of pilger mill electric drives, total energy losses were estimated for each cycle ( $T_c$ ) for different types of electric drives (direct-current drives, synchronous drives, drives with FRRM), based on equations given in [32]; the following possible control system structures were compared by energy efficiency: subordinate control scheme, two-zone speed regulation electric drive, proportionate control of armature flux and current; economic benefits of implementing the considered solutions were also evaluated. The chart in Figure 4 illustrates the results of comparing energy-saving reserves.

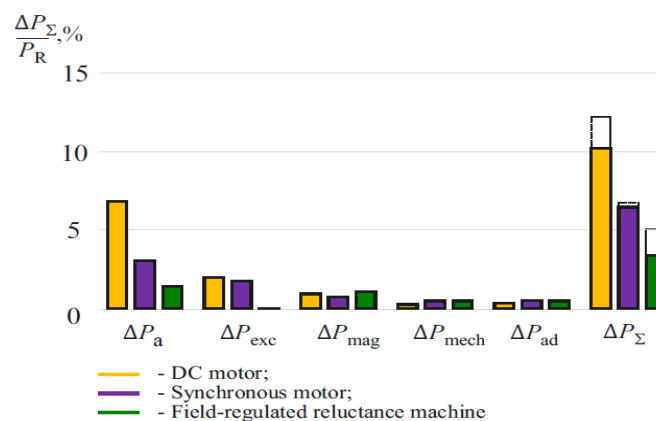


Figure 4. the chart of total losses and their component in various-type electric drives when comparing energy-saving control profiles

The diagram shows the distribution of total losses and their components in electromechanical converters upon control profiles implemented or likely to be implemented (dotted lines) and suggested in this paper (solid lines). In cases of load impacts, direct-current electric drives with subordinate control schemes,

by virtue of feedback communication on current and speed, allow for setting any required angle to a mechanical characteristic and thereby use the energy of an electric drive's flywheel in the most efficient way. In this case, current's root-mean-square value decreases, and so do losses.

Setting cutoff frequency  $\omega_c \approx 10$  rad/s in the speed control circuit with a proportional regulator decreases armature circuit's root-mean-square current in the mill 450's main drive's electric motor by 9%, which saves 100-150 thousand kWh per year in Figure 4. Further moderation of the mechanical characteristic is possible but not reasonable as it reduces mill's productivity. A special focus was on studying transient processes in electric drives of these mills, which was stipulated by the abrupt-variable nature of the static torque. The paper [33] calls attention to the energy efficiency of the proportionate control of armature flux and current and current for load-impact mechanisms.

In Figure 5, loss curves are shown for rolling motors, depending on the load torque and for various control methods. For electric drives based on synchronous motors, the character of dependencies is quite similar with slight qualitative differences. The highest energy effect was noted on limits of the load torque variation range. In the low-load area ( $M < 0.5$ ), proportionate control enables to sharply reduce the "constant" loss component, and also to make maximum use of the motor's power-to-size ration in overload areas ( $M > 1.5$ ).

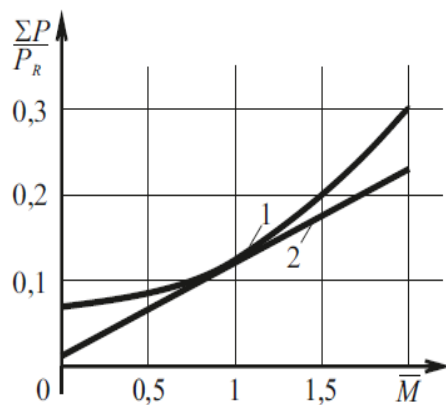


Figure 5. Relative Losses Depending on Load Torque in Direct-Current Motor at Constant Flux (1), at the Proportionate Control of Armature Flux and Current (2)

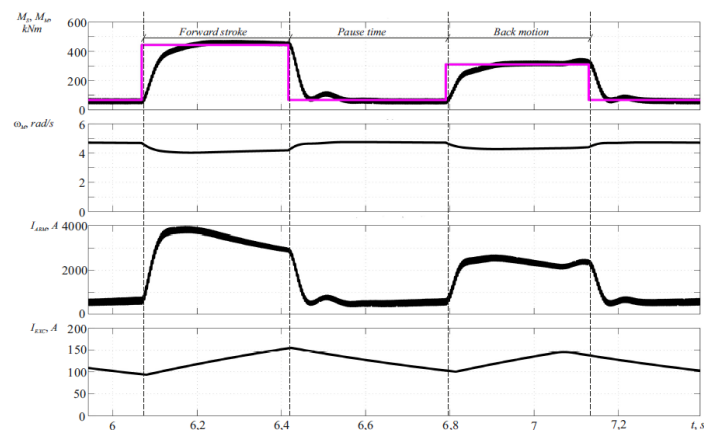


Figure 6. Transient processes in the electric drive of the cold rolling mill 450 based on a direct-current motor at proportional control of armature flux and current

The Figure 6 shows oscillograms of transient processes in the direct-current electric drive obtained through a math model plotted in *MatLab Simulink*, at the proportionate control of armature flux and current. The model demonstrates dependencies of armature circuit current  $I_a$  and excitation circuit current  $I_e$ , static load torque  $M_{st}$  and motor torque  $M_m$ , as well as angular spin rate  $\omega_{rot}$  on time. The calculation was conducted by means of the loss analysis block that enabled to pinpoint loss components in the direct-current electric drive based on obtained curves of transient processes.

Proportionate control requires excitation flux regulation both in statics and in dynamics. For pilger mill electric drives with relatively short rolling cycle, the necessity in flux control reflects on the value of energy saving. Thus, for direct-current and synchronous electric drives, armature flux and current control provides no energy-saving effect. The flux cannot keep up with the signal, and the electric drive operates in the middle area of  $\Delta P/P_R = f(M)$  in Figure 6, while the benefit of proportionate control may be gained when the operation time in limit zones of this characteristic hold the significant share of the cycle period. Such an effect is most clearly seen when  $T_{EC}$ , the time constant of motor's excitation coil, and  $T_{WC}$ , the time constant of the rolling work cycle, are similar. Besides, such a case leads to higher armature circuit current under load, which increases energy losses in Figure 6.

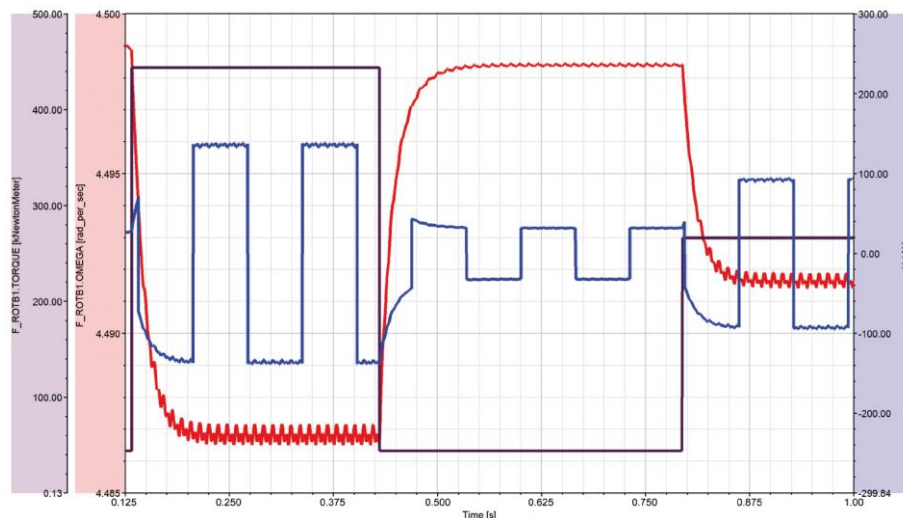


Figure 7. Transient processes in the electric drive of the cold rolling mill 450 based on FRRM

In the electric drive with FRRM, under uneven loads, energy can be significantly saved with the proportionate control when the rolling motor excitation current is regulated accordingly to the armature coil current. The Figure 7 provides oscillograms of transient processes in the electric drive with FRRM at the proportionate control and dependencies of the stator phase current, static load torque  $M_{st}$  and the angular spin rate on time. The calculation was conducted by means of the loss component determination unit in *Ansys Maxwell* according to equations given in [33].

The energy-saving effect in the system of proportionate control of armature flux and current makes itself felt enabling the electric drive working on loads corresponding to limit areas of the chart  $\Delta P/P_R = f(M)$ . Then, minimization of constant losses in the electric drive is applied in higher extent during the idle stroke, while root-mean-square current losses in the armature circuit have lower impact in case of overloads see in Figure 8.

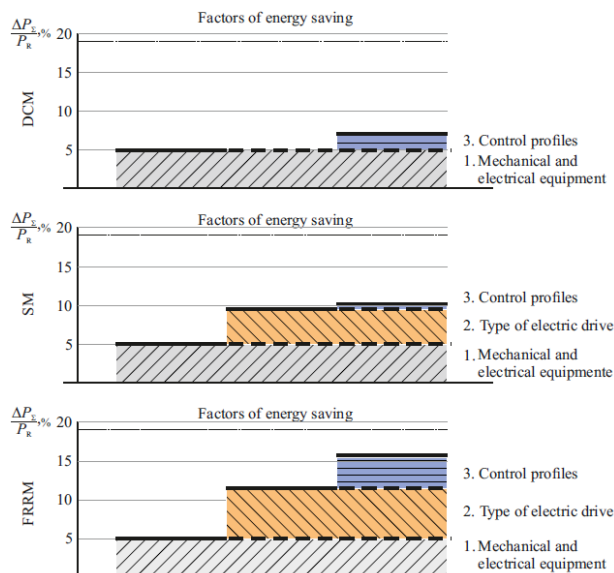


Figure 8. Factors of energy saving in pilger mill electric drive

In comparison to electric drives based on direct-current and synchronous motors, in the electric drive with FRRM the difference in quality of transient processes when high loads interchange with idle stroke areas solely provides energy saving up to 5% of the electric drive's power rating. In such a case,

armature coil generates the flux, as its time constant is significantly lower than the rolling work cycle period. Because of this, the electric drive operates in limit areas of the dependence  $\Delta P/P_n = f(M)$  for the much of the cycle period.

#### 4. CONCLUSION

As a result, the acute scientific and technical problem of increasing the energy-efficiency of electric drives of pilger rolling mills was solved, new principles and algorithms of controlling electrotechnical systems of rolling mills were suggested, capabilities and reserves of energy and resource supply by means of automated electric drives and control systems were unveiled. The analysis of technical process requirements for electric drives of pilger mills in the context of energy saving was conducted. Because of studying specifics of rolling technology, as well as mechanical and electrical equipment of pilger mills, it became clear the energy-saving method selection shall be based on the work mechanism's load chart. The classification of main energy-saving methods in electric drives of these mills was suggested.

Among electric drives of pilger mills operating on high torque loads and running on a short cycle comparable with the time constant of existing direct-current and synchronous motors, electric drives with FRRM showed the best energy-saving results due to higher quality of transient processes of armature and excitation current control. By means of math modeling, total losses and their components in the electric drive with FRRM were evaluated. Total energy losses per rolling cycle can be reduced by 12% (of the electric drive's power rating) by virtue of applying the energy-efficient electrical drive and recommended control profiles. Modernization of the rolling stand electric drive will enable to enhance energy efficiency. With that, based on calculations, the economic effect is reached through selection of the mechanical and electrical power equipment, implementation of the energy-efficient electromechanical converter, and application of energy-saving control profiles.

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#### REFERENCES

- [1] Petrov I. I., *et al*, "Special operating modes of the asynchronous electric drive", *Energy*, vol. 408, 1980.
- [2] Ilyinsky N. F., and V. V. Moskalenko "Electric drive: energy-saving: textbook a manual for students," *Publishing center "Academy"*, vol. 208, 2008.
- [3] Ilyinsky N. F., *et al*, "Energy-saving technical solutions in the electric drive," *Mosk. ENER. In-t*, vol. 64, 1985.
- [4] Leznov B. S., "Energy bases of the adjustable electric drive in pumping units," *water Treatment № 10 (58)*, pp. 14-31.
- [5] Leznov B. S., "Energy Saving automated systems in water supply and sanitation," *Water supply and sanitary technique No. 2*, pp. 15-21, 2004.
- [6] Kryukov O. V., "The analysis and technical implementation factors of efficiency of innovative solutions in electric turbochargers," *automation in industry, No. 10*, pp. 50-53, 2010.
- [7] Usynin U. S., *et al*, "Calculation of energy saving for a pumping station city water," *Electrical systems and complexes: interuniversity collection. SB. nauch. Tr. Vol. 6*, MGTU, 2001, pp. 137-140, 2001.
- [8] Braslavsky I. J., *et al*, "Energy efficiency laws of scalar frequency control of asynchronous electric drive," *Electrical engineering. No. 9*, pp. 44-47, 2012.
- [9] Shreiner R. T., and V. N. Poles "To the question of optimization of modes of variable frequency drives at a given load chart," *Adjustable electric drive of high inertial mechanisms. Chisinau: Shtiintsa*, pp. 119-129, 1980.
- [10] Shreiner R. T., and V. N. Poles "To the calculation of the minimum losses of the law of frequency control of an induction motor," *Asynchronous thyristor electric drive. Sverdlovsk, UPI* 1971, pp. 96-98, 1971.
- [11] Golovin V. V., *et al*, "Energy-Saving thyristor electric drives with automatic change of coordinates, a variable circuit excitation," *Electrician No. 4*, pp. 35-39, 2004.
- [12] Buryanov, V. F., *et al*, "Calculation of the engine power of the main drives of rolling mills," *Metallurgizdat*, vol. 360, 1962.



- [13] Hramsin V. R., *et al.*, "Energy Saving automated electric drives of the rolling units of production," in *1st Intern. scientific-pract. Conf. "INTEMET-2008"*, Sat. art. S-Pb 2008, pp. 134-139, 2008.
- [14] Hramsin V. R., "Energy saving thyristor electric drives of rolling mills," *Magnitogorsk: "MGU"*, vol. 180, 2013.
- [15] Kornilov G. P., *et al.*, "Improving the efficiency of heavy-duty electric arc furnace," *news of higher educational institutions. Electrician*. No. 1, pp. 55-59, 2009.
- [16] Usynin U. S., *et al.*, "Calculation of energy saving for a pumping station city water," *Electrical systems and complexes: interuniversity collection. SB. nauch. Tr. Vol. 6 Magnitogorsk: MGU*, pp. 137-140, 2001.
- [17] Kryukov O. V., "Energy saving & automation of electrical equipment of compressor stations," *Vector Tees*. Vol. 1, vol. 560, 2010.
- [18] Nikiforov G. V. and Zaslavets B. I., "Complex solution of problems of energy saving in the steel plant," *electrification of metallurgical enterprises of Siberia. Vol. 7. Tomsk*, pp. 72-80, 1997.
- [19] Oleynikov V. K. and V. Nikiforov V. "Differentiated indicators of efficiency of energy consumption in industrial production," *energy saving at the industrial enterprises: reports of the scientific-practical conference with international participation – Magnitogorsk*, pp. 92-95, 1997.
- [20] Giovanni De Filippis, *et al.*, "On the Energy Efficiency of Electric Vehicles with Multiple Motors," in *Vehicle Power and Propulsion Conference*. Oct 2016.
- [21] T. Ahonen, *et al.*, "Effect of Electric Motor Efficiency and sizing on the energy efficiency in pumping systems," in *Power Electronics and Applications*, 18th European Conference 2016. EPE 2016, ECCE 2016. Sept 2016.
- [22] M. A. Saidel, *et al.*, "Assessment and optimization of induction electric motors aiming energy efficiency in industrial applications," in *Electrical Machines XIX International Conference 2010. ICEM 2010*. Sept 2010.
- [23] A. Zabardast and H. Mokhtari, "Effect of high-efficient electric motors on efficiency improvement and electric energy saving," in *Electric Utility Deregulation and Restructuring and Power Technologies*, Third International Conference 2008. DRPT 2008. Apr 2008.
- [24] Dementyev, "Mathematical description of AC drives with brushless Converter in the steady state," *Electricity* No. 06, pp. 36-42, 2012.
- [25] Kopylov I. P., "Mathematical modeling of electrical machines: Textbook. For higher education institutions", *3rd ed. Rev. and extra. Higher. wk.*, vol. 327, 2001.
- [26] Dmitriev, V. A., "A Finite element model of electric machines by switching the flow to the study of dynamic modes," *Elektrotehnika* No. 03, pp. 7-13, 2012.
- [27] Law, D., "Design and Performance of Field Regulated Reluctance Machine", *IEEE Transactions on Industry Applications*, vol. 30 (5), pp. 1185-1192, 1998.
- [28] Law, J., "Magnetic Circuit Modeling of the Field Regulated Reluctance Machine", Part I: Model Development, *IEEE Transaction on Energy Conversion*, vol. 11 (1), pp. 49-56, 2000.
- [29] Grigorev, M. A., "Field regulated reluctance machine channel limits performance in speed and handling abilities: dis.-doctor.tech.Sciences: Specialty 05.09.03 – Electrical complexes and systems," – Chelyabinsk, – vol. 315, 2015.
- [30] Chuvakin, J. F., "Machines and Machines for steel pipe production: textbook," *Internet Engineering*, vol. 388, 2007.
- [31] Sheinman A. I., "The Album is the technical data of the individual electrical machines for drives of rolling mills second edition," *Moscow: GPI "Tyazhpromelektroproekt"*, vol. 363, 1968.
- [32] Usynin U. S., *et al.*, "Electric drive with field regulated reluctance machine for cold-rolling tubes," *Bulletin of the South Ural state University. A Series Of "Energy"*. Vol. 17 №16(275), pp.107-110. 2012.
- [33] Usynin U. S., *et al.*, "The Loss in the adjustable electric drives with different control laws," *Bulletin of the South Ural state University. A Series Of "Energy"*. Vol. 13. № 14(190), pp. 47-51, 2010.
- [34] Weh, H., "On the Development of Inverter Fed Reluctance Machines for High Power Densities and High Output", *Electrical Machines Institute of the Technical University of Braunschweig*, vol. 6, pp. 135-144, 1984.